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(54) **METHOD AND APPARATUS FOR RANGE RESOLVED LASER DOPPLER VIBROMETRY**

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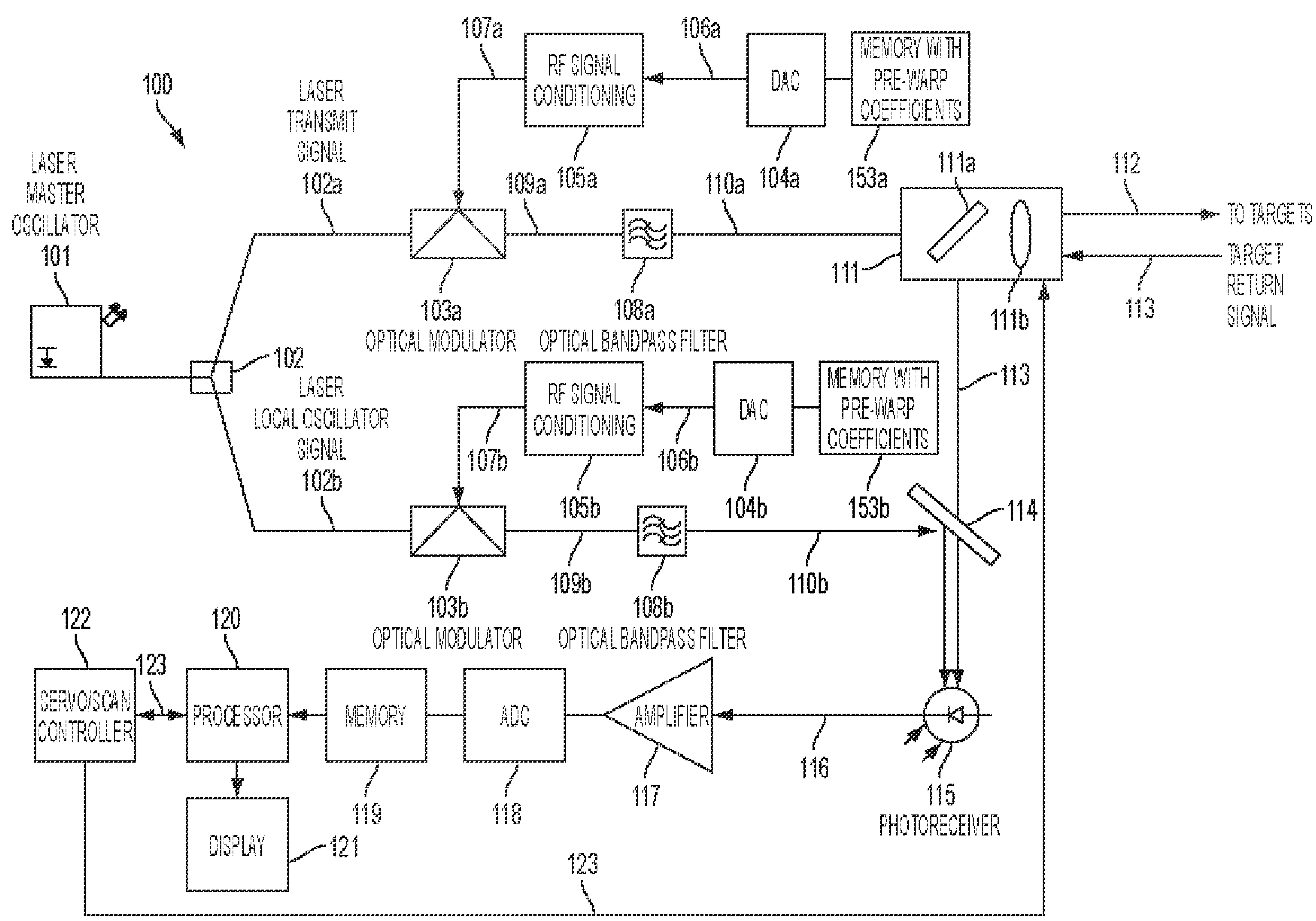
(57) **ABSTRACT**

In accordance with various aspects of the disclosure, a method and apparatus is disclosed for optically resolving one or more vibrating objects at an unknown distance using a vibrometer. The vibrometer includes a processor, a memory, and an optical device including a transmitter and a receiver. The method includes transmitting a first optical waveform having a linear frequency modulated chirp from the transmitter towards a region of space. At the receiver, a second optical waveform reflected from the one or more vibrating objects in the region of space is received. The vibrometer determines both a vibration frequency and a range information associated with the one or more vibrating objects based upon one or more characteristics of the second optical waveform. The determined vibration frequency and range information are stored in the memory for processing by the processor.



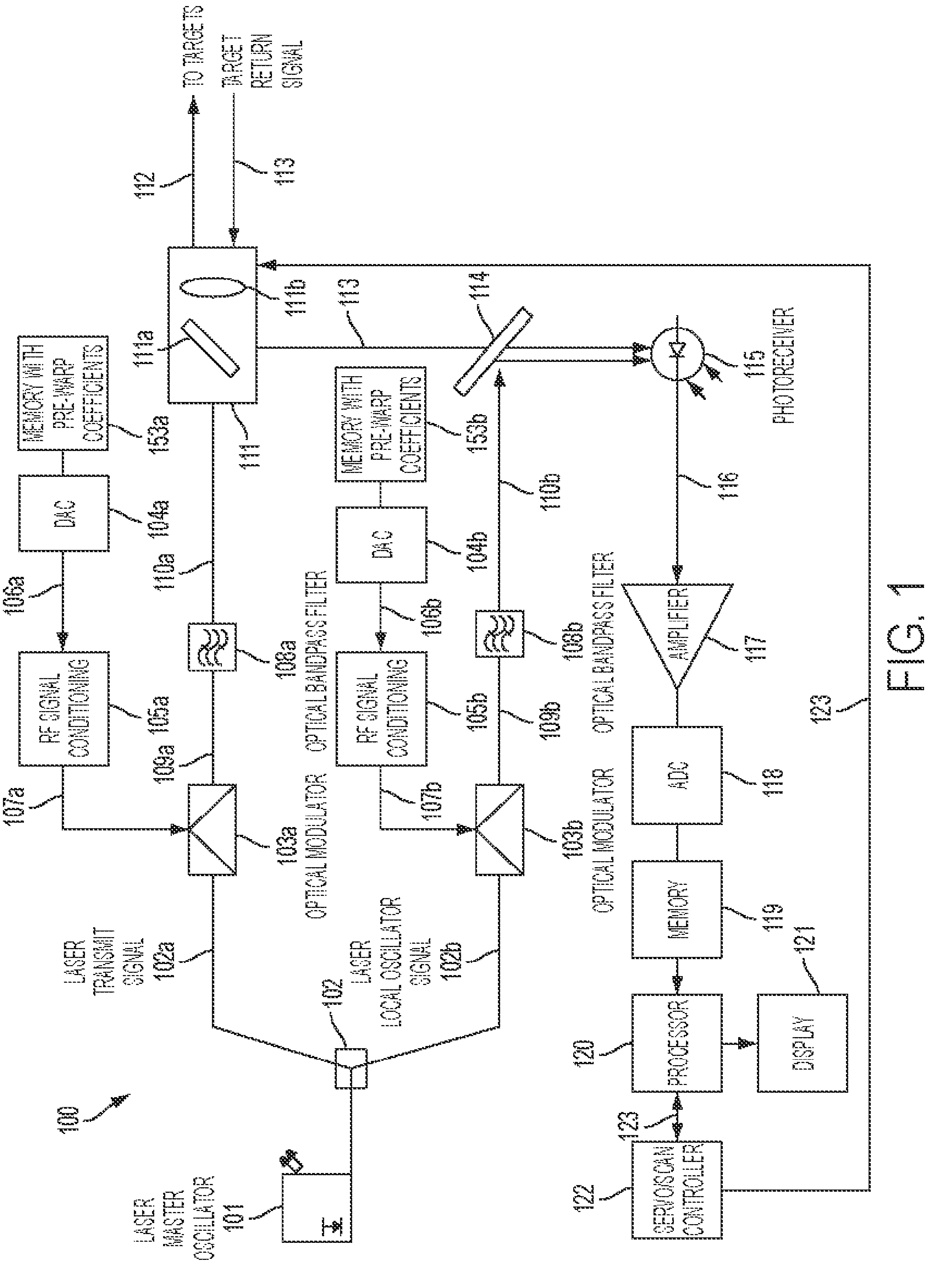

100
LASER MASTER OSCILLATOR
101
102
LASER TRANSMIT SIGNAL
102a
LASER LOCAL OSCILLATOR SIGNAL
102b
OPTICAL MODULATOR
103a
103b
DAC
104a
104b
105a
105b
RF SIGNAL CONDITIONING
106a
106b
107a
107b
OPTICAL BANDPASS FILTER
108a
108b
109a
109b
110a
110b
111
111a
111b
112
TO TARGETS
113
TARGET RETURN SIGNAL
114
115
PHOTORECEIVER
116
AMPLIFIER
117
ADC
118
MEMORY
119
PROCESSOR
120
DISPLAY
121
SERVO/SCAN CONTROLLER
122
123
MEMORY WITH PRE-WARP COEFFICIENTS
153a
153b

FIG. 1

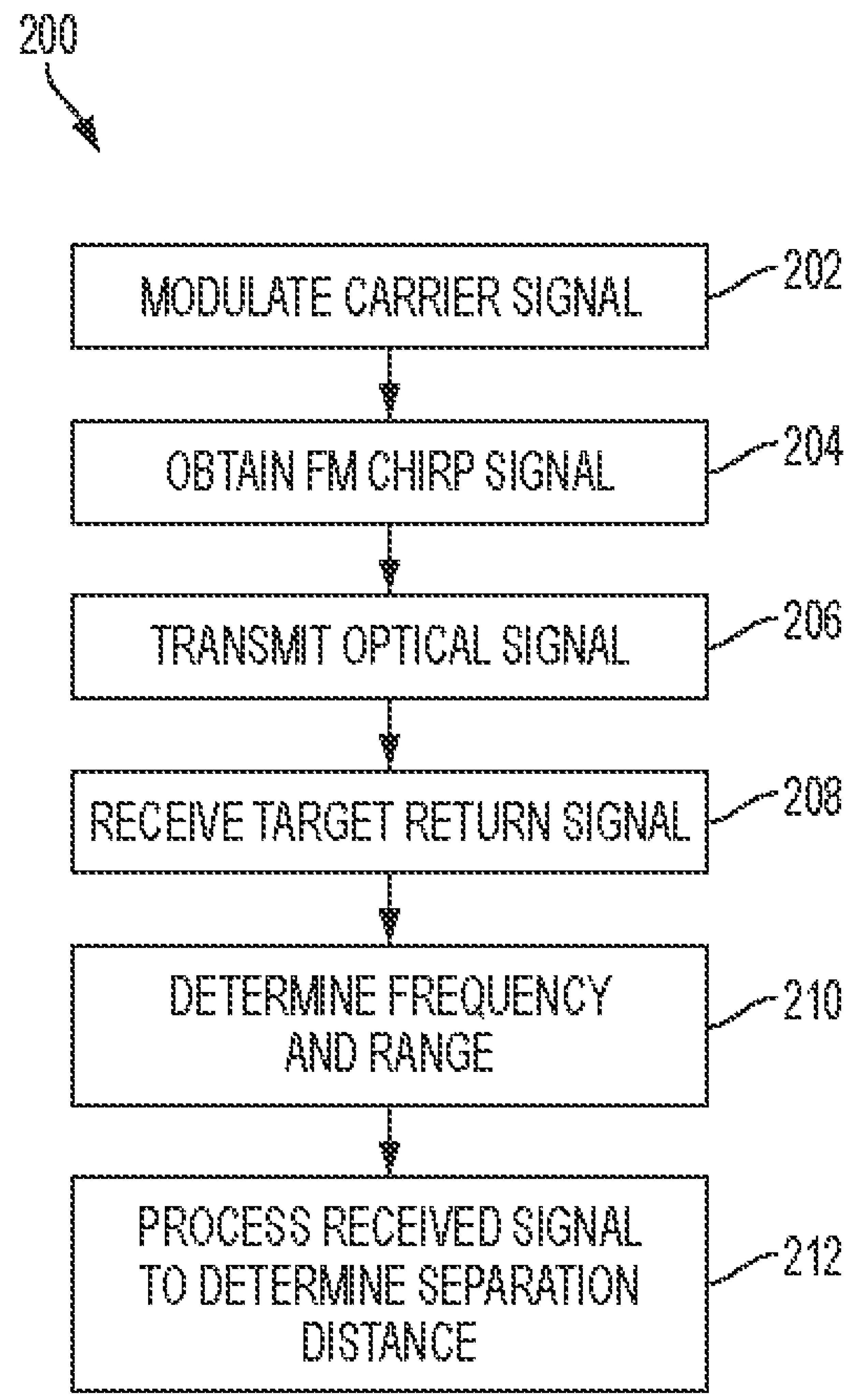

200
MODULATE CARRIER SIGNAL
202
OBTAIN FM CHIRP SIGNAL
204
TRANSMIT OPTICAL SIGNAL
206
RECEIVE TARGET RETURN SIGNAL
208
DETERMINE FREQUENCY AND RANGE
210
PROCESS RECEIVED SIGNAL TO DETERMINE SEPARATION DISTANCE
212

FIG. 2

METHOD AND APPARATUS FOR RANGE RESOLVED LASER DOPPLER VIBROMETRY

FIELD

[0001] This disclosure relates generally to the field of optics and, more specifically, to a method and apparatus for range resolved laser Doppler vibrometry.

BACKGROUND

[0002] Conventional laser Doppler vibrometers provide information regarding target vibration frequency and magnitude, but do not simultaneously provide any information about the range to target. Further, if there are multiple areas of a target vibrating at the same frequency, a conventional vibrometer is incapable of resolving the range between those vibrating areas. As a result, conventional laser Doppler vibrometers are able to accurately generate only a two-dimensional map of the vibrating object. What is needed is a laser Doppler vibrometer that simultaneously resolves vibrating objects at the same frequency but separated by a distance.

SUMMARY

[0003] In accordance with various embodiments of this disclosure, a method for optically resolving one or more vibrating objects at an unknown distance using a vibrometer. The vibrometer includes a processor, a memory, and an optical device including a transmitter and a receiver. The method includes transmitting a first optical waveform having a linear frequency modulated chirp from the transmitter towards a region of space. At the receiver, a second optical waveform reflected from the one or more vibrating objects in the region of space is received. The vibrometer determines both a vibration frequency and a range information associated with the one or more vibrating objects based upon one or more characteristics of the second optical waveform. The determined vibration frequency and range information are stored in the memory for processing by the processor.

[0004] In accordance with various embodiments of this disclosure, an optical system includes a vibrometer having a processor, a memory, and an optical device having a transmitter and a receiver. The transmitter is configured to transmit a first optical waveform having a linear frequency modulated chirp towards a region of space. The receiver is configured to receive a second optical waveform reflected from one or more vibrating objects in the region of space. The processor determines both a vibration frequency and a range information associated with the one or more vibrating objects based upon one or more characteristics of the second optical waveform. The processor resolves respective locations of each of the one or more vibrating objects based upon the determined frequency of vibration and the range information.

[0005] These and other features and characteristics, as well as the methods of operation and functions of the related elements of structure and the combination of parts and economies of manufacture, will become more apparent upon consideration of the following description and the appended claims with reference to the accompanying drawings, all of which form a part of this specification, wherein like reference numerals designate corresponding parts in the various Figures. It is to be expressly understood, however, that the drawings are for the purpose of illustration and description only and are not intended as a definition of the limits of claims. As used in the specification and in the claims, the singular form of "a", "an", and "the" include plural referents unless the context clearly dictates otherwise.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] FIG. **1** shows an example block diagram for an optical system for range resolved laser Doppler vibrometry, in accordance with an embodiment.

[0007] FIG. **2** shows a flowchart of a method for optically resolving one or more vibrating objects at an unknown distance using a vibrometer of the optical system of FIG. **1**, in accordance with an embodiment.

DETAILED DESCRIPTION

[0008] In the description that follows, like components have been given the same reference numerals, regardless of whether they are shown in different embodiments. To illustrate embodiment of the present disclosure in a clear and concise manner, the drawings may not necessarily be to scale and certain features may be shown in somewhat schematic form. Features that are described and/or illustrated with respect to one embodiment may be used in the same way or in a similar way in one or more other embodiments and/or in combination with or instead of the features of the other embodiments.

[0009] FIG. **1** shows an example block diagram for electro-optical system **100** for range resolved laser Doppler vibrometry, in accordance with an embodiment. Electro-optical system **100** includes, among other components, laser master oscillator **101**. Output of laser master oscillator **101** is optically split into two signal paths by beam splitter **102** or optical beam splitter **102**, providing optical beams of radiation **102***a* and **102***b*. In one embodiment, laser master oscillator **101** is a continuous wave laser outputting at a wavelength of 1550 nm to provide a narrow linewidth optical carrier as an output to beam splitter **102**, although other laser output wavelengths may be obtained using other types of laser oscillators, as can be contemplated by one of ordinary skill in the art.

[0010] Beam splitter **102** is optically coupled to optical modulators **103***a* and **103***b*. In one aspect, optical beam splitter **102** is a fused fiber splitter, with a 50/50 split ratio between respective signal paths of optical beams of radiation **102***a* and **102***b*, although other types of beam splitters with split ratios other than 50/50 could be used.

[0011] Electro-optical system **100** includes high-speed, digital memory **153***a*, **153***b* with time-domain samples of digital radio frequency (RF) waveform data stored thereupon, among other stored data. The time-domain samples have been modified using information obtained from pre-warp coefficients, described below, for compensating amplitude and phase distortions due to various components of optical system **100**. Waveform data in memory **153***a*, **153***b* represents the time-domain samples of a linear frequency-modulated (FM) chirp waveform and is provided to digital to analog converters (DACs) **104***a*, **104***b*, respectively.

[0012] DACs **104***a*, **104***b* are configured to generate analog RF waveforms **106***a*, **106***b*, respectively. DACs **104***a*, **104***b* are coupled to RF signal conditioning modules **105***a*, **105***b*, respectively, and output analog waveforms **106***a*, **106***b*, respectively. Analog waveforms **106***a*, **106***b* are amplified and frequency shifted by RF signal conditioning modules **105***a*, **105***b* to produce signals **107***a* and **107***b* with desired waveform bandwidth (BW) , which is related to the desired range resolution of targets resolved by optical system **100** in vibrometry application(s) by equation (1):

$$\Delta z = \frac{c}{2 * BW} \tag{1}$$

where Δz is the range resolution between the vibrating objects, c is the speed of light and BW is the RF modulation bandwidth of signals **107***a* and **107***b*, which is programmable.

[0013] RF conditioning modules **105***a*, **105***b* are electrically coupled to and provide RF conditioned signals **107***a* and **107***b* to optical modulators **103***a*, **103***b*, where RF conditioned signals **107***a* and **107***b* modulate optical carriers formed by optical beams of radiation **102***a*, **102***b*, respectively, and synthesize optical signals **109***a* and **109***b*, respectively possessing waveform bandwidth equivalent to the RF conditioned signals **107***a* and **107***b*. RF conditioning modules **105***a*, **105***b* include, among other components, RF amplifiers, bandpass filters, RF isolators and RF frequency doublers.

[0014] Optical modulators **103***a*, **103***b* are optically coupled to optical bandpass filters **108***a*, **108***b*, respectively. Optical bandpass filters **108***a* and **108***b* respectively remove any unwanted spurious optical signals from optical signals **109***a*, **109***b*, respectively. In one embodiment, by way of example only and not by way of limitation, optical modulators **103***a*, **103***b* are fiber coupled lithium niobate ($LiNbO_3$) amplitude modulators, commonly used in telecommunications systems. In one embodiment, optical modulators **103***a* and **103***b* are each Mach-Zehnder type modulators configured to generate or output a plurality of pulses as optical signals **109***a* and **109***b*, respectively, that are passed through optical bandpass filters **108***a* and **108***b*, respectively. Optical modulators **103***a*, **103***b* each output clean dual sideband suppressed carrier (DSB-SC) modulated linear FM chirp signals **109***a* and **109***b*.

[0015] Time-domain waveform data in memories **153***a*, **153***b* is configured such that the stored data samples contain one or more representations of distortion that may be encountered by the signals in optical system **100** and therefore compensate for phase and amplitude distortions in electrical and optical devices in the signal path from DACs **104***a*, **104***b* to RF Signal Conditioning modules **105***a* and 105*b*, respectively, to optical modulators **103***a* and **103***b* and optical bandpass filters **108***a* and **108***b*, producing near theoretically perfect modulated optical single-sideband suppressed carrier (SSB-SC) modulated linear FM chirp signals **110***a* and **110***b*. This technique is known as pre-warping and is described, for example, in U.S. patent application Ser. No. 12/793,028, entitled "METHOD AND APPARATUS FOR SYNTHESIZING AND CORRECTING PHASE DISTORTIONS IN ULTRA-WIDE BANDWIDTH OPTICAL WAVEFORMS," filed Jun. 3, 2010, incorporated by reference herein in its entirety.

[0016] In an embodiment, optical modulators **103***a* and **103***b* are configured to produce modulated optical signals **109***a*, **109***b*, respectively that are dual-sideband suppressed carrier (DSB-SC) waveforms with linear frequency modulated (FM) chirp. DSB-SC linear FM chirp optical waveforms **109***a* and **109***b* are passed through optical bandpass filters **108***a* and **108***b*, respectively. By way of example only and not by way of limitation, optical bandpass filters **108***a* and **108***b* may be Fiber Bragg Gratings configured as optical bandpass filters reflecting the optical sideband of interest while removing the other optical sideband and residual optical carrier. The result of optical filtering are optical single-sideband suppressed carrier (SSB-SC) linear FM chirp signals **110***a* and **110***b* created from optical carriers **102***a* and **102***b*, respectively, provided by laser master oscillator **101**. In this embodiment, optical FM chirp signal **110***a* is intended to provide target signal **112** and signal **110***b* to provide a local oscillator signal for heterodyne detection, as described below.

[0017] Signal **110***a* is provided to optical device **111** configured to optically shape and steer signal **112** towards one or more targets using, for example, gimbaled mirror **111***a* and telescope **111***b*. Optical device **111** is configured as a transceiver, i.e., a transmitter for FM chirp signal **110***a* and a receiver for one or more target return signals **113** received after reflection from one or more targets (stationary and/or vibrating). Although referred to as optical device **111**, optical device **111** may include additional optical, electrical, electro-optical, mechanical, electro-mechanical, and opto-mechanical components for beam shaping and steering, as can be contemplated by one of ordinary skill in the art in view of this disclosure. When targets are present, optical device **111** receives one or more target return signals **113** with frequency and phase signatures of the vibrating targets embedded therein. By way of example only, the one or more vibrating objects may be part of a vibrating object body (e.g., parts of a truck).

[0018] Target return signal **113** is steered toward and provided to beam combiner **114**, where target return signal **113** is optically heterodyned with optical FM chirp signal **110***b* acting as a local oscillator signal. Photoreceiver **115** is optically coupled to optical device **111** via beam combiner **114**, and receives a combination of FM chirp signal **110***b* and one or more target return signals **113**. In one embodiment, photoreceiver **115** and beam combiner **114** may be integrated with optical device **111** to form the receiver for one or more target return signals **113**. Photoreceiver **115** is arranged to heterodyne FM chirp signal **110***b* and one or more target return signals **113**. Since heterodyning of such signals is known to those of ordinary skill in the art, it will not be described herein. Photoreceiver **115** may be a photoreceiver designed for a spectral response over a wide range of optical wavelengths such as those provided by Newport Corporation of Irvine, Calif., for example. In one embodiment, optical device **111**, beam combiner **114** and photoreceiver **115** are jointly referred to as a receiver for the vibrometer formed by optical system **100**.

[0019] Output of photoreceiver **115** is heterodyned electrical RF signal **116**. In this embodiment, the total target round trip distance is less than the coherence length of master oscillator laser **101**. Thus, signals **110***a*, **110***b*, and **113** are mutually coherent and have a deterministic phase relationship. This provides for coherent, heterodyne detection of one or more target return signals **113** at photoreceiver **115**. One or more target return signals **113** have respective frequency shifts (denoted by AO associated with target velocity changes (e.g., resulting from vibration of the targets) and are related to the target velocity by the Doppler equation:

$$\Delta f = 2 * V * \cos(\Theta) / \lambda \tag{2}$$

[0020] where V is the target velocity, Θ is the angle of incidence between the optical beam (i.e., target signal **112**) and a surface normal to the vibration direction, and A is the optical wavelength of target signal **112**. Such frequency shifts result in frequency changes in heterodyne signal **116**. Such measurement of Doppler shift using equation (2) is therefore, used to determine the vibration frequency information of the one or more vibrating objects.

[0021] Thus heterodyned electrical signal **116** has frequency and phase information characteristic of one or more vibrating objects of a vibrating body. The frequency and phase information is used to resolve range and physical separation between two or more targets in a region of space towards which target signal **112** is steered or directed. Photoreceiver **115** is electrically coupled to amplifier **117** that receives heterodyned electrical signal **116**. In one embodiment, amplifier **117** can be a low noise amplifier (LNA), although other types of suitable amplifier known to those of ordinary skill in the art may be used. Amplifier **117** is electrically coupled to analog to digital converter (ADC) **118** that converts the amplified analog output of amplifier **117** into a digital signal for storage in memory **119**. It is to be noted that memory **119**, **153***a*, and **153***b* may be conventional memory units such as Random Access Memory (RAM), or other forms of tangible optical, magnetic, or electrical memory known to those of ordinary skill in the art.

[0022] Stored digital signal in memory **119** is then provided to processor **120** that processes the digital signal to determine the frequency changes in the digitized RF signal that are proportional to the target vibration. By scanning optical device **111** with scan/servo controller **122** that sends scan angle data **123** to optical device **111** and processor **120**, digital data outputted from memory **119** can be associated with scan angles commanded by scan/servo controller **122**. Using the associated data, processor **120** can, for example, generate a three dimensional range resolved map of targets for displaying on display **121** that shows spatial resolution between targets vibrating at the same or different frequencies in a target object, although such data may be used for other purposes such as enhancing performance of optical system **100**.

[0023] In one embodiment, one or more components of optical system **100** are arranged as a vibrometer configured to simultaneously resolve range and frequency information of two or more vibrating object or targets based upon the specific arrangement of optical and electrical components in optical system **100**, and utilizing equations (1) and (2). In another embodiment, optical system **100** forms a vibrometer. For example, the two or more vibrating objects can be two or more different parts of the same vibrating body that are physically separated but are vibrating at the same frequency. Such vibrating frequency may be same as or different from an overall vibrating frequency of the vibrating object. For example, the vibrating object may be a truck hidden under an optically opaque cover, and having a front and a rear part vibrating at the same frequency. Using the examples described herein, physical separation and frequency information of the vibrating targets is determined.

[0024] FIG. **2** shows a flowchart for method **200** for optically resolving one or more vibrating objects at an unknown distance using a vibrometer of optical system **100** of FIG. **1**, in accordance with an embodiment.

[0025] Method **200** begins at step **202** where laser master oscillator signals **102***a* and **102***b* from laser master oscillator **101** are modulated using RF conditioned signals **107***a* and **107***b*, respectively, having pre-warp compensation from coefficients stored in memories **153***a*, **153***b*, respectively at optical modulators **103***a* and **103***b*, respectively. Pre-warp compensation stored in memories **153***a* and **153***b* removes amplitude and phase distortions present in signal chains of optical system **100** resulting in clean optical SSB-SC modulated linear FM chirp signal **110***a* prior to transmission and optical SSB-SC modulated linear FM chirp signal **110***b* (used as local oscillator signal) prior to heterodyning with target return signal **113**.

[0026] In step **204**, as a result of modulation by optical modulators **103***a* and **103***b*, DSB-SC linear FM chirp optical waveforms **109***a* and **109***b* are obtained at respective outputs of optical modulators **103***a* and **103***b*.

[0027] In step **206**, after filtering by optical bandpass filter **108***a* and passing through optical device **111** configured as a transceiver, target signal **112** having a linear FM chirp is transmitted towards one or more targets in a region of space. In parallel, linear FM chirp optical waveform **109***b* is optical bandpass filtered by optical bandpass filter **108***b* to obtain optical SSB modulated linear FM chirp signal **110***b* to be used for heterodyning, as discussed below. In one embodiment, transmitted target signal **112** comprises a plurality of pulses that are frequency modulated portions of the carrier.

[0028] In step **208**, when one or more targets are present, target return signal **113**, upon reflection from the one or more targets, is received at optical device **111**, configured as a receiver. Target optical return signal **113** contains modified frequency and phase resulting from the vibrating objects from which return signal **113** was reflected.

[0029] In step **210**, using optical local oscillator signal formed by FM chirp signal **110***b* to create a heterodyne signal at photoreceiver **115**, phase and frequency of one or more target return signals **113** are extracted and converted into equivalent electrical target return signals **116**. One or more target electrical return signals **116** are amplified by amplifier **117**, and digitized by ADC **118**, resulting in a time-domain series of digital data samples stored in digital memory **119**. Digital data samples stored in memory **119** contain the modified frequency and phase information resulting from the interaction of the optical target signal **112** and target vibrational behavior.

[0030] In step **212**, the time domain samples in digital memory **119** are processed using radar range-Doppler techniques to locate targets in range. Such techniques can be implemented, for example, using processor **120**. Observation of a particular target's change of frequency and phase from pulse to pulse, per equation (1) enables the extraction of the target's time-Doppler history which can be analyzed via power spectral density methods to compute the target's vibration signature. Processor **120** can be programmed to apply techniques to data samples stored in memory **119** for processing and further analysis, for example, to generate a three-dimensional map that resolves the distance between the targets along with their respective vibration frequencies. The separation distance between the vibrating objects is determined by processor **120** based upon an amount of frequency modulation of signal **116**, according to equation (1) above.

[0031] Using aspects of this disclosure, various applications can be advantageously implemented. For example, the disclosure can be applied to long-range airborne coherent Ladar imaging. For example, improved imaging resolution of a Ladar compared to MWIR or LWIR sensors at similar range can be achieved using the disclosure. Another application includes using coherent Ladar waveforms with large time-bandwidth to offer superior resolution capabilities to existing technologies.

[0032] Although the above disclosure discusses what is currently considered to be a variety of useful embodiments, it is to be understood that such detail is solely for that purpose, and that the appended claims are not limited to the disclosed embodiments, but, on the contrary, are intended to cover modifications and equivalent arrangements that are within the spirit and scope of the appended claims.

What is claimed is:

1. A method for optically resolving one or more vibrating objects at an unknown distance using a vibrometer, the vibrometer comprising a processor, a memory, and an optical device comprising a transmitter and a receiver, the method comprising:

transmitting a first optical waveform having a linear frequency modulated chirp from the transmitter towards a region of space;

receiving, at the receiver, a second optical waveform reflected from the one or more vibrating objects in the region of space;

determining, by the vibrometer, both a vibration frequency and a range information associated with the one or more vibrating objects based upon one or more characteristics of the second optical waveform; and

storing, in the memory, the determined vibration frequency and range information for processing by the processor.

2. The method of claim **1**, wherein the determining comprises heterodyning, at a photoreceiver in the receiver, a third optical waveform with the second received optical waveform to produce a heterodyned signal used for the determining.

3. The method of claim **2** further comprising:

compensating, at the vibrometer, the first optical waveform for distortion prior to the transmitting, and the third optical waveform prior to the heterodyning, using one or more representations of the distortion stored in the memory.

4. The method of claim **2**, wherein during said heterodyning, the third waveform is provided as a local oscillator signal to the photoreceiver.

5. The method of claim **2**, wherein a phase relationship between the first, the second, and the third optical waveforms is deterministic.

6. The method of claim **1**, wherein the vibrating objects are separated by a distance that is determined at the receiver based upon an amount of frequency modulation of the first waveform.

7. The method of claim **1**, wherein the one or more vibrating objects are a part of a vibrating object body.

8. The method of claim **1**, wherein the determining comprises measuring a Doppler shift of the received second optical waveform to determine the vibration frequency information of the one or more vibrating objects.

9. The method of claim **1**, wherein the first and third optical waveforms each comprise a plurality of pulses produced using a pair of Mach-Zehnder modulators.

10. The method of claim **1**, wherein the one or more characteristics of the second optical waveform include at least one of frequency and phase.

11. An optical system, comprising:

a vibrometer comprising a processor, a memory, and an optical device comprising a transmitter and a receiver, wherein:

the transmitter is configured to transmit a first optical waveform having a linear frequency modulated chirp towards a region of space;

the receiver is configured to receive a second optical waveform reflected from one or more vibrating objects in the region of space; and

wherein the processor:

determines both a vibration frequency and a range information associated with the one or more vibrating objects based upon one or more characteristics of the second optical waveform, and

resolves respective locations of each of the one or more vibrating objects based upon the determined frequency of vibration and the range information.

12. The optical system of claim **11**, wherein the vibrometer comprises a laser master oscillator configured to generate a third optical waveform that is heterodyned at the receiver with the second received optical waveform to produce a heterodyned signal used by the processor to determine the vibration frequency and range information.

13. The optical system of claim **12**, wherein the vibrometer is configured to compensate the first optical waveforms for distortion prior to a transmission by the transmitter, and the third optical waveform prior to the heterodyning at the receiver, using one or more representations of the distortion stored in the memory.

14. The optical system of claim **12**, wherein a phase relationship between the first, the second, and the third optical waveforms is deterministic.

15. The optical system of claim **11**, wherein a separation distance between the vibrating objects is determined at the receiver based upon an amount of frequency modulation of the first waveform.

16. The optical system of claim **11**, wherein the one or more vibrating objects are a part of a vibrating object body.

17. The optical system of claim **11**, wherein the vibrometer is configured to measure Doppler shift of the received second optical waveform to determine the vibration frequency information of the one or more vibrating objects.

18. The optical system of claim **11**, wherein the one or more characteristics of the second optical waveform include at least one of frequency and phase.

19. The optical system of claim **11**, wherein the vibrometer comprises a pair of Mach-Zehnder modulators, and wherein the first and third optical waveforms each comprise a plurality of pulses produced using the pair of Mach-Zehnder modulators.

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